

Flow, spectra and HBT radii in heavy-ion collisions

Piotr Bożek^{*†}

IFJ PAN, Kraków, Poland

E-mail: piotr.bozek@ifj.edu.pl

Iwona Wyskiel

IFJ PAN, Kraków, Poland

The expansion of the fireball created in relativistic heavy ion collisions is described using the 3 + 1D hydrodynamical model. Experimentally observed transverse momentum spectra at different rapidities, elliptic flow and HBT correlations of produced particles can be reproduced. We give estimates of shear viscosity corrections at freeze-out, which we find important only for the elliptic flow coefficient.

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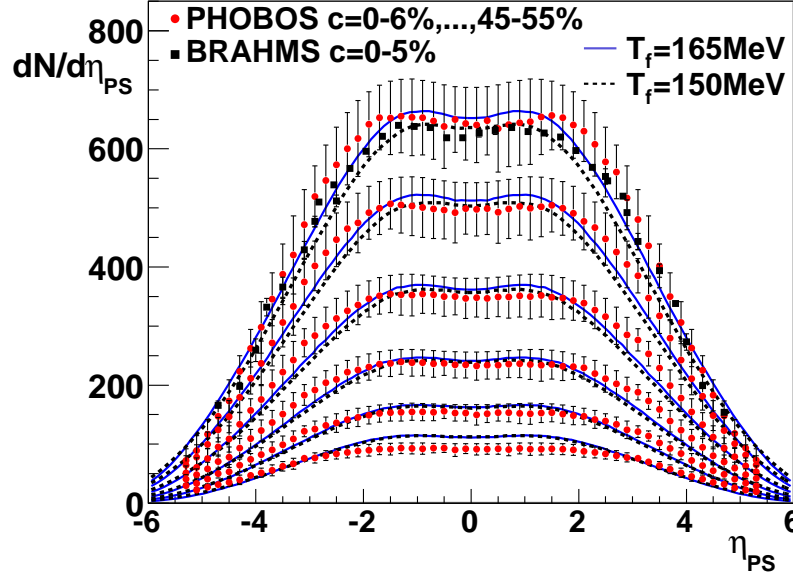


Figure 1: Distribution of charged particles in pseudorapidity at different centralities, calculated from the 3+1D hydrodynamic model [2], compared to experimental data of BRAHMS and PHOBOS Collaborations.

The expansion of the dense and hot fireball created in relativistic heavy-ion collisions can be described using relativistic hydrodynamics [1]. We perform 3 + 1D hydrodynamic simulations of Au-Au collisions at the highest RHIC energy $\sqrt{s} = 200\text{GeV}$ [2]. Compared to existing calculations [3], we use a very short initial time $0.25\text{fm}/c$ and a realistic equation of state of dense matter [4]. The absence of a soft point in the equation of state leads to a rapid expansion of the system, resulting in a strong build up of the transverse flow. The initial energy density profile in the transverse plane is taken from the Glauber Model, and the initial distribution in space-time rapidity is adjusted to reproduce the measured charged particle distributions (Fig. 1).

Hydrodynamic equations of a perfect fluid $\partial_\mu T^{\mu\nu} = 0$ are solved for each impact parameter. The shape of the constant temperature ($T_f = 150\text{MeV}$) freeze-out hypersurfaces, as well as the final collective velocities of the fluid are exported to a statistical emission and resonance decay code THERMINATOR [5]. The THERMINATOR code generates complete events including statistically emitted particles from the fireball. Calculated transverse momentum spectra of produced particles follow very well the experimental results [2]. It is true for particle emitted at central rapidities for different collision centralities, up to 50%; also the agreement with the data at forward/backward rapidities is striking (solid lines in the left panel of Fig. 2) and proves that the hydrodynamic expansion model of the fireball combined with statistical emission applies in a broad range of rapidities. Microscopically it means that approximate local equilibrium is reached and maintained during a sizable time-span of the collective expansion. HBT correlation radii [6] calculated from the model are within 10% from the measured values (right panel of Fig. 2) [2]. A short initial time of the evolution requires a narrow initial distribution in space-time rapidity, this results in a strong suppression of elliptic flow when approaching the fragmentation regions (Fig 3).

We estimate the effects of viscous corrections on particle emission. Using the velocity flow

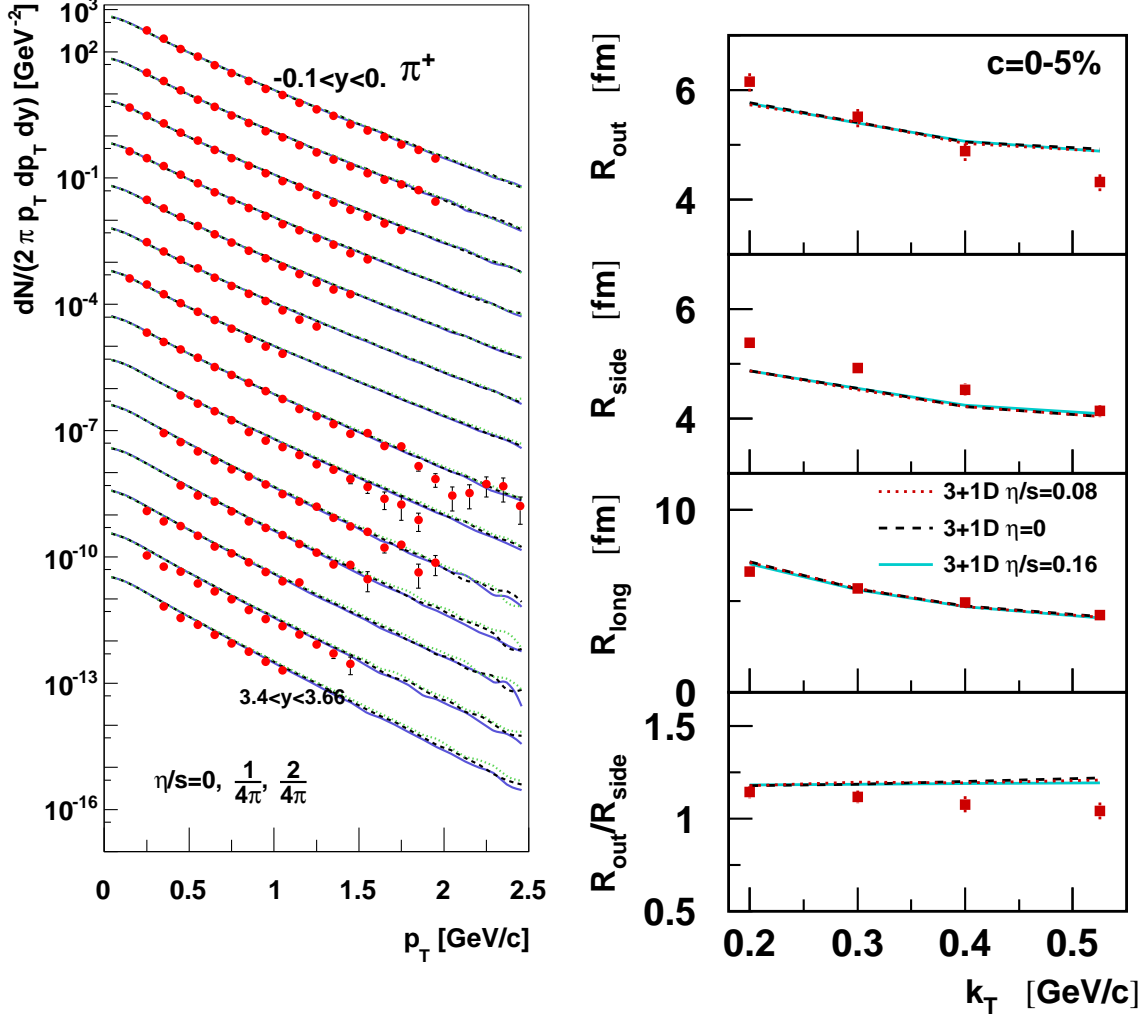


Figure 2: (Left panel) Transverse momentum spectra of π^+ at different rapidities for three different shear viscosity coefficients at freeze-out ($\eta/s = 0, \frac{1}{4\pi}, \frac{1}{2\pi}$, solid, dashed, and dotted lines) compared to BRAHMS Collaboration data. (Right panel) HBT correlation radii for different strengths of shear viscosity corrections at freeze-out, STAR Collaboration data.

obtained in a $3+1D$ perfect fluid dynamics we calculate nonequilibrium corrections to the Cooper-Frye formula from shear viscosity [7]. Modified momentum distributions are implemented in the statistical emission code. Results range from, no appreciable modifications of the transverse momentum spectra for $p_\perp < 1.5\text{GeV}$ and central rapidities, up to a 30% increase at rapidity $y = 3.5$ and $p_\perp = 3\text{GeV}$ for $\eta/s = 0.16$. The HBT radii are not sensitive at all to the shear corrections at freeze-out if the flow remains unchanged (Right panel in Fig. 2).

A significant reduction of the elliptic flow is induced by stress corrections (Fig. 3). The reduction is 20% at central rapidity and goes up 60% at pseudorapidity 4 for $\eta/s = 0.16$. This observation agrees with the results of Ref. [8], where dissipation from hadronic rescattering was found to be important at large rapidities. This effect modifies strongly the dependence of the elliptic

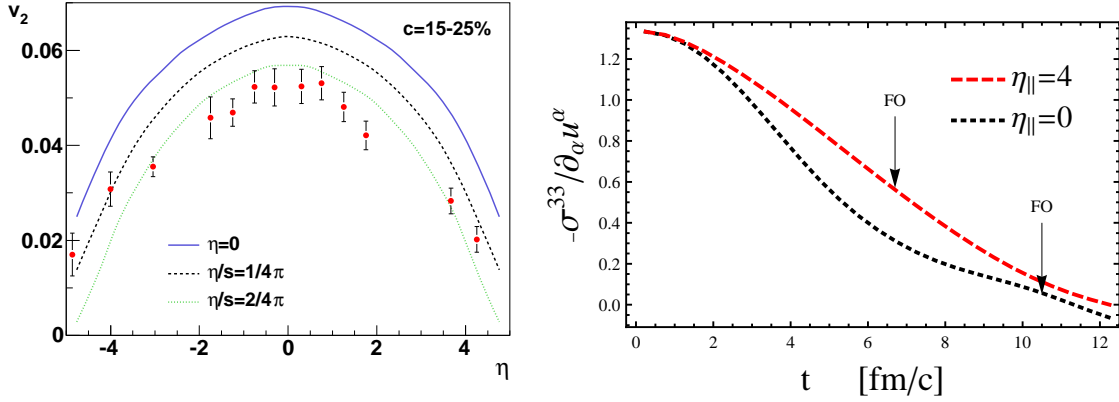


Figure 3: (Left panel) Elliptic flow coefficient for charged particles as function of pseudorapidity for three different viscosity coefficients at freeze-out, compared to PHOBOS Collaboration data. (Right panel) Ratio of the stress velocity gradient to the overall expansion rate as function of time at two space-time rapidities. The arrows indicate the time of the freeze-out.

flow of charged particles on pseudorapidity. From the ratio $\frac{-\sigma^{33}}{\partial_\alpha u^\alpha} = \frac{-2\nabla^3 u^3 + 2/3 \Delta^{33} \partial_\alpha u^\alpha}{\partial_\alpha u^\alpha}$ presented in the right panel of Fig. 3 we expect large shear viscosity corrections at large rapidities, whereas at central rapidities correction from bulk viscosity (proportional to $\partial_\alpha u^\alpha$) could also be important. The approximate agreement of perfect fluid calculations with the data on elliptic flow is accidental. Moreover shear viscosity modifies also the longitudinal acceleration of matter [9] changing the distributions in Figs. 1 and 3.

Summarizing, we find good agreement of the results of 3 + 1D perfect fluid hydrodynamics with the measured transverse momentum spectra, HBT radii and elliptic flow. Estimates of shear viscosity effects show that the last observable is not robust and a reliable estimate thereof requires the use of a fluid expansion model including shear and bulk viscosity.

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